HEAT TREATMENT OF TWO CHROME - VANADIUM STEELS

BY

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AN INVESTIGATION OF THE EFFECTS OF HEAT TREATMENT UPON SOME OF THE PHYSICAL PROPERTIES OF TWO CHROME-VANADIUM STEELS

A THESIS

PRESENTED BY

RICHARD F. ROTHWELL

TO THE

PRESIDENT AND FACULTY

OF

ARMOUR INSTITUTE OF TECHNOLOGY

FOR THE DEGREE OF

BACHELOR OF SCIENCE IN CIVIL ENGINEERING

HAVING COMPLETED THE PRESCRIBED COURSE OF STUDY IN

CIVIL ENGINEERING

MAY 29, 1913

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PREFACE

A demand has arisen within the last few years for steels of superior qualities to those which were being supplied for use in tools, automobiles and electrical, hydraulic and steam appliances. This demand has resulted in numerous and extensive investigations into the nature of steel, its defects and their elimination. The result is that at the present time many special steels may be obtained, all of which are superior to the steels formerly used, but each one is particularly suited to the class of work for which it was made. The most important feature of these is that while they come out of the rolls or from under the hammer a high grade steel yet they may be greatly improved by submitting them to the proper heat treatment. The term "proper" is used advisedly and furnishes the basis of this investigation. According to the theory of heat treatment which has been developed it would be an easy matter to obtain by accurate methods the cooling curve of a piece of steel and from it outline the method of heat treatment which would most completely develop its desirable properties. In practice the theory works out only approximately and it becomes necessary to run a series of tests to show the possibilities of the steel in question. Such a series forms an interesting study and not only links the theory and practice together but supplies the opportunity for

the development of unsuspected and valuable results, for while it is true that a great deal of work has been done along this line yet much more remains to be done before the field is covered. For these reasons it was decided to investigate the effects of heat treatment upon the physical properties of one of the comparatively new steels, namely, chrome-vanadium.

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THEORETICAL CONSIDERATIONS

It has long been known that if a piece of steel was heated to a certain temperature and quickly cooled its physical properties would be greatly changed. The reasons for this phenomena have been brought forth by recent investigations. If the temperature rise of a piece of steel be recorded continuously as it is uniformly heated from atmospheric temperature to 1000° C it will be found that at one, two or three different temperatures, depending upon the carbon content of the steel, a retardation of the sensible temperature rise takes place. If a similar record be taken as the steel cools, retardations of the sensible temperature fall will be found to occur slightly below the points previously noted. Experiments have shown that each retardation is caused by the absorption or evolution of heat by the steel, due to the changing of its structure. The retardations are called "critical temperatures". The structures which exist in and above the range of critical temperatures have different physical properties from the normal structure at atmospheric temperature. One of them is harder and tougher than the normal structure, one is softer, and another is non-magnetic. Cooling the steel very quickly from a temperature in or above the critical range will partially preserve the existing structure and consequently the steel will possess the properties of that structure at atmospheric temperature to a greater or less extent, depending upon the rate of cooling and the specific

effect of the chemical constituents in hastening or retarding the change. The process is called "quenching". Steel is often quenched in water but some oils give better results. After a piece of steel has been quenched it is too hard and brittle for most purposes. Heating it to some temperature below the critical range and allowing it to cool in air will make it softer and more tough. This operation is called "drawing". The final result will be that the hardness, elastic limit and ultimate strength of the treated steel will be greater than they were before it was treated. This brief outline gives the working basis of all heat treatments, but the best results to be obtained can only be ascertained by making a series of tests covering the critical range and extending beyond it.

A satisfactory description of the structural changes involved in the foregoing processes, their causes and effects, would fill many pages as may be determined by referring to Professor Albert Sauveur's book on the Metallography of Iron and Steel, and as that is not the purpose of this investigation it will not be inserted here.

OUTLINE OF WORK

Three distinct operations are involved in determining the possibilities of subjecting a given steel to heat treatment, namely, preliminary investigations, heat treatment and testing. The preliminary work will consist of making chemical analyses of the material to be used and determining its critical temperatures. It might be

thought that the ladle analysis furnished with a high grade steel is sufficiently accurate for experimental purposes. Experience has shown that it is not and consequently a special analysis of every bar to be used must be made in order to insure the use of the material desired. The outline of the effects of heat treating showed that it is essential to determine the location of the critical range before planning the quenching temperatures to be used. The work of heat treating is quite simple, providing the proper apparatus is available, but it must be watched carefully; ~~because~~ all variations which might produce peculiar results should be noted, otherwise the tests would be worthless. The treated specimens may be subjected to a variety of tests. Those which give the most reliable and important information are the tension and hardness tests. Torsion and bend tests have been found to give results which are approximately proportional to the results of tension tests. Dynamic stress tests give very interesting and important results but are hard to make accurately. Magnetic tests are becoming almost essential because steels of low and high permeability and of low and high hysteresis loss are coming into great demand in the manufacture of electrical machinery. For this reason the magnetic properties of all special steels should be known. The steel should also be studied under the microscope as the changes of structure with the different treatments may be followed out and used later as a basis for studying similar steels of unknown heat treatment. After considering the foregoing tests it was decided that

the best results would be obtained if tension and hardness tests were made of all of the different heat treatments, and magnetic tests and micro-photographs were made of those treatments which were likely to give the most marked differences in results.

APPARATUS

Some of the apparatus used are of standard designs, familiar to all who are interested in testing materials, and require no detailed description, but a description of a few of the instruments which are not so well known may be of interest.

Furnace. The most important factor to control in this work is the furnace temperature. For this reason a Hoskins Electric Furnace, Type F. C., was selected and the results were all that could be desired. The maximum current required was 750 amperes at 20 volts. This was supplied by an 1100 volt generator and stepped down to the required voltage. The upper photograph on Plate No. 1 shows the furnace in the background. The heavy leads seen in the lower right hand corner of the picture are attached to large carbon electrode holders beneath the furnace. The electrodes are an inch and a quarter in diameter. They project through the bottom of the furnace, one on each side, and are in contact with carbon plate resistances which are made up of plates two inches wide, eleven inches long and one-quarter of an inch in thickness. The plates are in vertical piles which form the sides of the interior of the furnace. Two large carbon plates rest on top of the piles and complete the circuit. The carbon plates are set inside of heavy fire-

brick walls which are contained in a steel jacket and are very effective in preventing radiation. The counter-balanced door is also made of fire-bricks which are held in a steel casing. The size of the available heating space is five by six by thirteen inches. The advantages of this type of furnace were found to be: a comparatively small loss of heat by radiation, uniform heating of the interior, and easy regulation of the temperature. The latter was accomplished by means of hand screws beneath the furnace which controlled the pressure of the electrodes on the carbon plates.

Temperature Indicator. Another essential feature of good temperature control is the temperature indicator. A Whipple Temperature Indicator was used. It is also shown in the upper photograph of Plate No. 1. The fire-end is of the compensated electrical resistance type having two platinum wires inclosed in a porcelain tube at the end which is exposed to the temperature to be measured; a long steel tube provides a suitable protection and support for the other end. Four leads connect the fire-end with the indicator box, shown in the foreground of the picture. This box contains two batteries, a differential galvanometer, contact key and a temperature scale and slide wire contact on a revolving drum. The indicator operates on the principle of the Wheatstone Bridge. To measure the temperature of the fire-end the four leads are connected to their proper terminals and the drum is revolved until the galvanometer shows no deflection when the contact key is closed. The temperature is then given by the figure on

the drum which appears under a stationary mark.

Extensometer. The determination of the elastic limit of a piece of steel when tested in tension is of primary importance and consequently the best method available should be used. The extensometer shown in the photograph on the middle of Plate No. 1 was used. It consists of a horizon - al bar supporting two vertical graduated arcs at the ends, two vertical pieces of spring steel near the middle, and each piece of the spring steel has a center point on it near the bottom. One of the pieces is fixed to the bar, but the horizontal position of the other is controlled by a thumb screw. Two long pointers, each provided with a knife edge perpendicular to its axis at one end, are also part of the extensometer. When a test piece is in the testing machine the instrument may be attached to it by forcing the center points into it near the lower shoulder by means of the thumb screw and inserting the knife edges of the pointers between the test piece and the springs. Notches are provided in the springs for the knife edges, and when they are accurately placed the pointers are held firmly in position. When the pointers are adjusted to the zero marks of their respective scales the distance between the knife edges and the center points is exactly two inches. The instrument is now in position to indicate elongations of the test piece within the standard two-inch length. The smallest division on the arc corresponds to an elong - ation of one one-thousandth of an inch, and tenths of the division may be estimated. The average of the readings on both scales will be the true value of the elongation of the specimen.

Fluxmeter. Plate No. 2 shows awiring diagram of the fluxmeter used. This instrument is a very accurate indicator of the magnetic flux passing through the bar being tested. A study of the diagram will show the principle upon which it is operated. The rod to be tested is inserted in the soft iron yoke and is firmly held in place by tight-fitting split collars at each end. The collars are secured in place by means of thumb screws; their purpose is to reduce the error due to an air gap to a minimum. The coil C_1 is supplied with current from a battery, the rheostat R_1 regulates the amount of current, and the double throw snap switch its direction. The resistance box R_3 and the rheostat R_2 regulate the amount of current supplied to the vertical swinging coil C_2. When the bar is inductively magnetized by the current passing through C_1 the magnetic circuit is completed through and confined to the yoke because of its large size and high permeability. The torque exerted by this flux cutting the field of the vertical coil at right angles twists the coil; the amount of twist of the vertical coil is proportional to the flux in the rod as the current in the coil is maintained at a constant value. The flux indicator F is rigidly attached to the swinging coil and passes over a scale which is calibrated, so that, with proper current regulations, the permeability of the rod may be read directly.

Micro-Photographic Apparatus. The lower photograph on Plate No. 1 shows the micro-photographic apparatus used. This is a slightly modified form of the Le Chatelier inverted microscope which is made by Ernst Leitz, of Wetzlar, Germany.

Tension Testing Machine. An Olson 60,000 pound machine was used for making the tension tests. It was particularly suited for the work in hand for two reasons: The maximum load required was about 50% of its total capacity and consequently the machine was as sensitive as could be desired, a large wheel was provided on the main shaft so that loads could be applied by hand when desired.

Hardness Testing Apparatus. Hardness tests were made with the Brinnel machine under standard conditions, namely; with a pressure of 3,000 kg. on a ball 10 mm. in diameter. The hardness of the various specimens was also measured with the Shore Scleroscope.

MATERIALS

Steel. It was first thought that it might be a good plan to make a crucible steel to test but this idea was abandoned. In the first place, the only furnace available that would give the required temperature had too small a capacity. In the second place, the results obtained would not be of commercial value, for experience has shown that crucible steel made in small quantities always gives much better results than the open hearth or electric steels made in large quantities. Consequently, several bars of open hearth chrome-vanadium steel of two different carbon contents were secured. In one set the carbon was supposed to be between .25 and .35, and in the other between .40 and .50. The bars were an inch and a quarter in diameter although the largest size required was three-quarters of an inch. The large size was used for the purpose of reducing the tests more nearly to a commercial basis as

large bars are frequently used but they give lower results when tested than the smaller ones do. It was decided that the easiest method of keeping a record of the test pieces would be to number them consecutively as they were cut from the bars, recording the numbers of the bars from which they were cut and the kinds of tests for which they were to be used. This information is contained in Table No. 1. It will be noticed that many numbers are omitted. These were given to specimens used for purposes which do not enter into this investigation. The pieces which were to be used for chemical analyses and for cooling curves were four inches long, the magnetic test pieces were twelve inches long, and the tension tests were six inches. The length required for the standard tension test is five inches but the extra inch was provided so that it could be cut off after the pieces were treated and used for the hardness tests and for examination with the microscope.

METHODS AND RESULTS

Chemical Analysis. The specimens for chemical analysis were turned over to the laboratory to be analyzed by the standard methods used in commercial work. The results are given on the page containing Table No. 1. Those for specimen No. 81 went astray; it was of .40 to .50 carbon content.

Calibration of Pyrometer. To insure the obtaining of correct temperatures it was necessary to calibrate the indicator. After the apparatus was connected up the fire-end was packed in melting ice. A small variable resistance was adjusted and clamped in such a position that the galvanometer

gave no deflection when the circuit was closed and the zero mark of the scale was directly below the fixed reference point. When the fire-end was next put in steam under atmospheric pressure the instrument read 100.0°. The fire-end was thenput in the vapor of boiling sulphur and the instrument read 440.1°. The barometer reading at the time this work was done was 747.7 mm. Water boils at 100.0° and sulphur boils at 444.7° under the standard pressure of 760mm. After making the necessary corrections for the difference in barometric pressure the instrument was found to register .46° too nigh at 100° and 3.5 degrees too low at 444.7°. This corresponds to a drop of approximately 1° for each 100° beyond the point of boiling water. As this error is within the range of variation of the furnace for any desired constant temperature it will not need to be taken into account in the following work, but it should be kept in mind if making a comparison between the results of this investigation and another.

Heating and Cooling Curves. When taking data for heating and cooling curves two pyrometers are required to give accurate results. They should be arranged so that the differences in temperature between the sample under examination and a neutral body in the same furnace may be recorded, either on a photographic plate or by taking readings at short intervals. In this way any effects caused by non-uniform heating or cooling would be eliminated. This method was not available for the present work so a less accurate method had to be used. Each specimen was an inch and a quarter in diameter and four inches long. A five-eighths inch

hole three inches deep was drilled in one end. The specimen was supported in the furnace about three inches above the bottom, the fire-end of the pyrometer was inserted in the test piece to almost the full depth of the hole, and it was prevented from coming in contact with the steel by a mica packing at the outer end. The temperature was then recorded every fifteen seconds as the piece was slowly heated from 480° to 1100° and slowly cooled from that temperature to 550°. The Curves on Plate No. 14 are plotted from the data taken, the ordinates being used to indicate the temperatures, and the elapse of time from the beginning to the end of the test is plotted on the abscisses. It will be noticed that the method used will not differentiate between a non-uniform sensible temperature variation and absorptions and evolutions of heat by the steel. For this reason the less intense critical points are not clearly represented on the curves. The lowest critical point on cooling, called Ar_1, is the one of maximum intensity, and its position is quite definitely located on each of the cooling curves. It occurs at 707° in the lower carbon steels and at 698° in the steels of higher carbon. Comparing this result with the diagram of critical ranges in Sauveur's Metallography of Iron and Steel, Lesson 7, page 11, we find that the presence of the chromium and vanadium in the steels under consideration does not effect the location of Ar_1. With this as a basis to work from and with the diagram mentioned as a guide, most of the other critical points were selected and marked, but it must be remembered that only the points Ar_1 have been definitely

located by the method used. From a consideration of the slopes of the curves it will be seen that the critical ranges extend to about 780°. Knowing this fact, we may now proceed to the heat treatment of the steel.

Heat Treatment. The structure of the steel before it is subjected to quenching has a marked influence upon the final results, therefore it is necessary to anneal the steel to give all of it the same structure and to secure results which will be comparable. This is done by soaking it at a temperature a little above the critical range for a short time and then allowing it to cool in air. 840° was selected as the annealing temperature of the low carbon and 820° for the high carbon steel. It was decided to quench the steels from 790°, 825°, 850°, 875°, and 900° as experience has shown that the most effective quenching temperature will be found within 100° of the upper point of the critical range. 450°, 500°, 550°, and 600° were selected as the drawing temperatures. One specimen was to be treated for each one of the combinations of quenching and drawing temperatures; for example, one was to be quenched at 790° and drawn at 450°, another quenched at 790° and drawn at 500°, another quenched at 790° and drawn at 550°, etc. In addition, two specimens of each steel were to be annealed but not quenched. This made a total of twenty-two tension specimens of each steel that would be required to cover the proposed field.

A small steel frame was made to hold the specimens in the furnace, it served the double purpose of keeping the pieces off of the bottom, and of increasing the capacity

of the furnace. Eight was found to be the maximum number of pieces which could be accomodated at one time and allow a good circulation of heat. They were arranged in two tiers, four in a tier. A space above the center of the frame was provided for the fire-end. When the specimens were put in a cold furnace the temperatures for the various treatments were controlled in the following manner: To anneal; the heat was brought up to the annealing temperature in about one hour and held there for thirty or forty minutes, the pieces were then taken out and cooled in air. To quench; the heat was raised to 700° in about one hour and held there for ten minutes, it was then raised to the quenching temperature in about twenty minutes and held there for half an hour. The pieces were then taken out and immediately plunged in the quenching oil. To draw; the heat was brought up to the drawing temperature in about forty-five minutes and held there for twenty minutes, the pieces were then cooled in air. The foregoing applies to those pieces which were the first to be taken out of the furnace. The furnace was loaded at the start of each heat and the pieces that had to be heated to higher temperatures were raised to, and soaked at, those temperatures after the others were taken out. When the pieces were put in a hot furnace the time of heating was shortened by about thirty minutes. Tables No. 2 and No. 3 contain a record of the time and temperature of each individual heat treatment. The temperature of the quenching oil before and after quenching is also recorded.

It was not thought necessary to make a magnetic test

of each of the heat treatments which the tension tests were subjected to, but instead ten pieces of each steel were allotted to cover a wider range. The quenching temperature plays a more important part than the drawing temperature in determining the magnetic qualities. For this reason six of the tests were quenched at 750°, 790°, 825°, 850°, 900°, and 950°; all of them were drawn to 450°. Three more were quenched at 850° and drawn to 500°, 550°, and 600°; the tenth was annealed but it was not quenched. As the magnetic tests were twelve inches long it was necessary to heat them about an hour longer than the tension tests. Each one had to be reversed in the furnace while it was soaking at the required temperature as the end near the door was cooler than the rest of the bar.

In all of the heat treating no important deviations from the proposed work occurred.

Hardness Tests. After the six inch specimens were treated an inch was sawed off of the end of each. An automatic hack saw was used so that excessive friction and the resulting heating effect would be avoided. The short pieces were used for the hardness tests after one end of each had been ground down on a polishing disk and given a smooth finish with fine emery cloth. Each piece was tested five times with the scleroscope, the hammer being directed once to the center and once to the center of each quarter of the circle. The average of the five results is considered to be the scleroscope hardness of the specimen. Tables No. 2 and No. 3 contain the results of these tests. The specimens were resurfaced after testing.

The Brinnel test was also made five times on each specimen, once in the center and once in the center of each quarter. The diameters of the impressions were measured with a glass scale under a low power microscope. The resulting pressures in kilograms per square millimeter of the area depressed were obtained from a table supplied with the instrument. The average of the five results for each specimen is considered to be the Brinnel hardness. Tables No.2 and No. 3 contain the results of these tests.

It was noted, in looking over the results of these tests, that all of the specimens had a very uniform hardness over the entire cross section. This indicates that they were heated to the same temperature throughout when making the heat treatments. A comparison of the Brinnel and scleroscope hardnesses will show that the Brinnel tests follow up very closely what might be expected from the theoretical considerations involved while the scleroscope tests are somewhat erratic and hard to be accounted for. This might be expected from the fact that the personal equation is quite a factor in making the scleroscope tests but it is entirely eliminated in the Brinnel method.

Tension Tests. The only feature of special interest in connection with making the tension tests is the use of the extensometer in determining the elastic limit. This instrument has been previously described. After it was fixed in position on a test piece a load of four thousand pounds was applied by means of the hand wheel and the elongation was read on the extensometer. Two small telescopes mounted on a standard facilitated the taking of these readings. Then loads in increments of two thousand pounds

were applied and the corresponding elongations were recorded. This was continued up to a short distance beyond the elastic limit, then the extensometer was taken off and the test was completed in the usual way. When two persons are working together the jump of the pointer at the elastic limit can be easily detected, but with only one making the test the determination is not quite so accurate. The results of the tension tests are contained in Tables No. 2 and No. 3. Plates No. 11 and No. 12 show partial stress-strain curves for these tests. They were plotted for the purpose of determining the locations of the elastic limits. It is interesting to note the different ways in which the various specimens "let go" at the yield point.

Now that the results of the physical tests have been obtained it might be well to insert at this point a discussion on the method to be used in plotting them. It will be conceded that that system will be most desirable which will most completely cover the work performed, providing it does not sacrifice clarity for scope. To cover the entire field of heat treatment for any specific set of results, such as the hardness figures, three variables must be introduced into the scheme, one of which depends upon a combination of the other two. This has been accomplished on Plate No. 5 and some of the succeeding plates. On Plate No. 5 the axis of abscisses has been selected for the drawing temperatures and the axis of ordinates for the quenching temperatures. The chart was then laid out as follows: At the intersection of 450° drawing temperature

and 790° quenching temperature was placed the hardness figure for the steel subjected to that treatment, at the intersection of 500° and 790° was placed the hardness figure for the steel subjected to that treatment and so on until the hardness of every piece of treated steel was to be found in its proper place on the chart. As the temperature increments used in the heat treating are so small it will not introduce any serious error to assume that the variation in hardness in any given increment is uniform. For example, as it was found that a piece quenched at 825° and drawn at 450° had a hardness of 213, and a piece quenched at 825° and drawn at 500° had a hardness of 208, then a piece quenched at 825° and drawn at 480° would have a hardness of 210. For convenience of reference the increments were divided up in this way into divisions of every 10 points of hardness. Then it was an easy matter to draw a line through the points of equal hardness and the result is given on the chart. The lines show at a glance just how the hardness has advanced with the increasing quenching and drawing temperatures. In this way charts of the linesof equal hardness (Plates No.3 and No.7), lines of equal elastic limit(Plates No. 4 and No.8) and of equal maximum strength (Plates No.5 and No.9) were prepared. Lines of equal elongation and reduction of area could not be drawn because theydid not occur in any order with respect to the treatments, but the figures are given on Plates No. 6 and No. 10.

A study of these charts shows that for good results it is essential that the quenching temperature for both

steels should be above 850°, and the best results will be obtained if the steel is quenched at 900° and drawn at 450°.

The only abnormal result obtained in the physical tests was the hardness of specimen No. 4 which was quenched at 790° and drawn at 500°. Nothing unusual could be found in the heat treatment of this particular piece so the very low result must be attributed to some unknown cause. Aside from this the results were very satisfactory and followed out closely what was to be expected from the theoretical considerations involved.

Magnetic tests. The magnetic test specimens were turned down to one-half inch in diameter over their entire length. They were tested in the fluxmeter previously described. The current in the swinging coil was adjusted to the proper value and held constant throughout the entire series of tests. When a specimen was first put in the instrument it was thoroughly magnetized by slowly increasing the magnetizing current and reversing it many times. The ~~the~~ permeability was read for the maximum magnetizing force. It was then decreased to zero in small increments and the corresponding permeabilities were read. The magnetizing force was then reversed and increased in small increments to a maximum negative value, the permeability being recorded for each change. The results of these tests are plotted on Plate No. 13. The area in the upper left hand quarter between the curve and the axes is proportional to the amount of work required to take the magnetic remanence out of the steel. The harder the steel is the greater is the demagnetizing force which it requires. The results show that the presence of chromium

and vanadium in such small quantities do not affect the magnetic properties of the steels as the results obtained from ordinary steels are quite similar to them. The range of temperatures covered is evidently above that required to preserve the non-magnetic structure, because the flux produced by the maximum magnetizing force is practically the same for every specimen.

CONCLUSIONS

The principal object of this investigation was to determine to what extent the physical properties of the steels under consideration would be affectd by heat treatment. The charts show that in no instance did the treated steel fail to give better results than that which was not treated. The highest maximum strength was obtained from those steels whichwere quenched at 900 and drawn to 450 . They also had a good elongation and reduction of area, but these were improved at the expense of the strength by drawing the steels quenched at 900 back to 500 . Therefore the two foregoing treatments are to be recommended as producing the most satisfactory results.

The magnetic tests showed very uniform results, and consequently if another investigation of the magnetic properties were to be made it should involve a far greater range of quenching temperatures, and little attention need be paid to the variations in drawing temperatures.

Taking the entire investigation into consideration, it might be said that the results were very uniform in their accordance with the theory of heat treatments and no unusual results were obtained.

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation of the assistance rendered by his instructors and friends.

This investigation has been carried out under the supervision of Mr. H. B. Pulsifer, Instructor in Metallurgy. He has contributed much time and many valuable suggestions to the work.

The professors of the Department of Electrical Engineering have gladly offered their services whenever called upon.

The author is also greatly indebted to his friends in the Illinois Steel Company who have given the advice and assistance necessary to place this investigation upon a commercial basis.

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Vanadium Steel, by J. Kent Smith, Official Proceedings of the Railway Club of Pittsburg, Sept., 1907. Abstracts: Many dynamic stress tests have shown that vanadium steels hold up better than other steels. ... Chromium and vanadium are used together because chromium increases the static strength and vanadium increases the dynamic strength. This article also mentions that the Firminy Steel Works, made the first important tests of the effect of vanadium on steel, but the element did not receive much attention until after Prof. Arnold made an extensive investigation of the subject in 1900.

Results of Guillet; Journal of the Iron and Steel Institute, 1906, Vol. 2, page 15. Abstracts: The following groups were investigated;

Group Micro-Structure Carbon.20% Carbon .80%

Group	Micro-Structure	Carbon .20%	Carbon .80%
1	Pearlite	V < .7	V < .5
2	Pearlite&Carbide	.7< V < .5	.5 < V < .7
3	Carbide	V > .3	V > .7

Group 1. Tensile strength and elastic limit rise rapidly with increase of V. Elongation and reduction of area slowly decrease but preserve relatively high values. Brittleness does not increase but hardness increases rapidly.

Group 2. An increase of V decreases tensile strength and elastic limit, increases elongation and reduction of area, and rapidly diminishes resistance to shock.

Group 3. High elongations and reductions of area, but very brittle.

Journalof the Iron and Steel Institute; Carnegie Scholarship Memoirs, Vol. 1, 1909, page 33. Abstract: In steel of low Vanadium content the vanadium is completely dissolved by ferrite, the solution becoming saturated at .6%. Above this vanadium unites with pearlitic carbon to form vanadium carbide which increases with the increase of vanadium.

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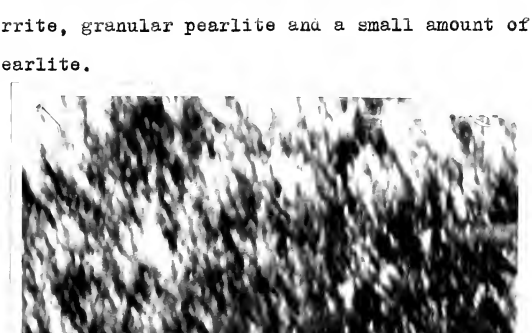
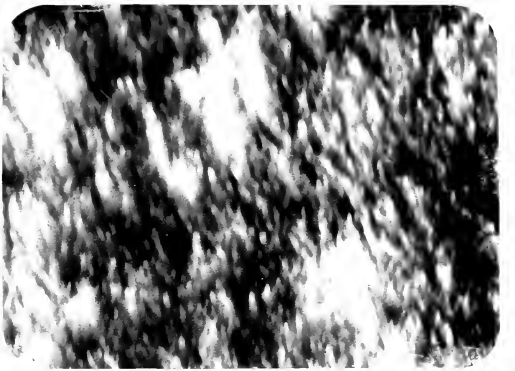
MICRO-PHOTOGRAPHS

The micro-photographs on the following pages do not show the structures as clearly as might be desired but they will serve to give an idea of the changes produced by the various heat treatments. The structures were so fine that it was thought the best results would be obtained by using a magnification of one thousand diameters. This necessitated an exposure of from one to two seconds, and undoubtedly such long exposures provided ample opportunity for vibrations to blur the negatives. The specimens were polished in the usual way and etched for forty seconds in a solution of picric acid in alcohol.

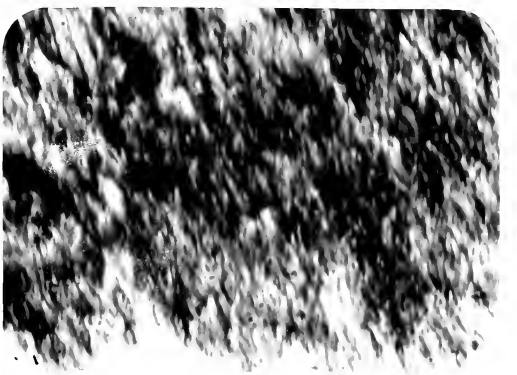
No. 1 - .29 carbon. Annealed at 840 . Magnified 1000 diameters Free ferrite, granular pearlite and a small amount of laminated pearlite.



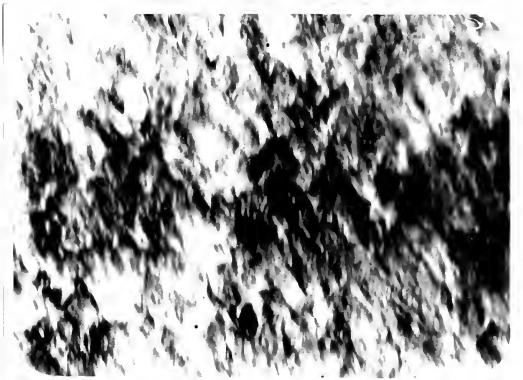
No. 8 - .29 carbon. Annealed at 840 , quenched from 790 , drawn to 450 . Magnified 1000 diameters. Free ferrite, granular pearlite and a small amount of laminated pearlite.



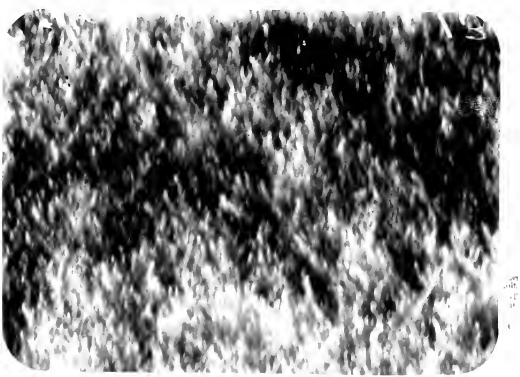
No. 6 - .29 carbon. Annealed at 840 , quenched from 825 , drawn to 450 . Magnified 1000 diameters. Free ferrite, granular pearlite and sorbite.



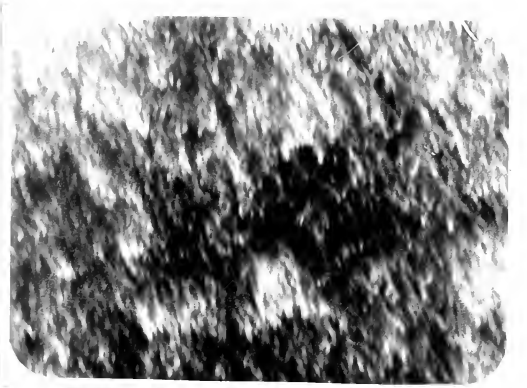
No. 11 - .29 carbon. Annealed at 840 , quenched from 850 , drawn to 450 . Magnified 1000 diameters. Small amount of free ferrite and granular pearlite, large amount of sorbite.



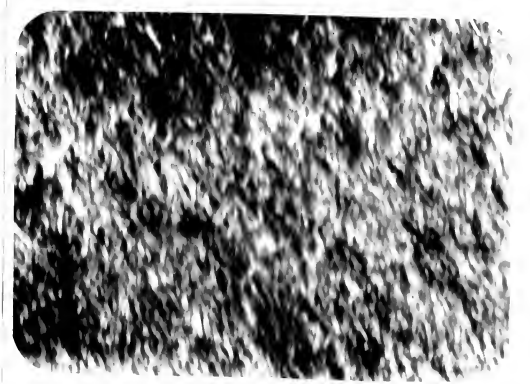
No. 12 - .29 carbon. Annealed at 840 , quenched from 825 , drawn at 500 . Magnified 1000 diameters. Small amount of sorbite,laminated and granular pearlite, free ferrite.



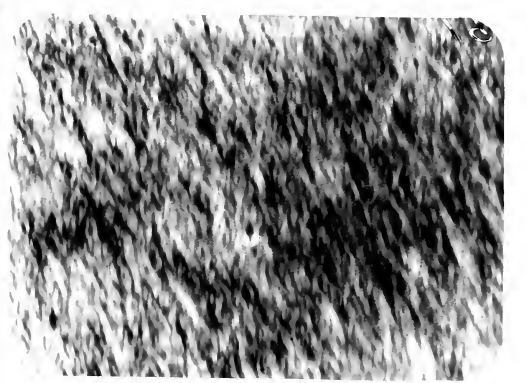
No. 13 -.29 carbon. Annealed at 840 , quenched from 850 , drawn to 550 . Magnified 1000 diameters. Small amount of free ferrite, large amount of granular pearlite.



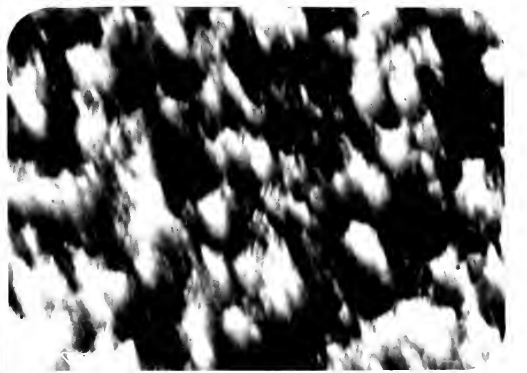
No. 14 - .29 carbon. Annealed at 640 , quenched from 850 , drawn to 600 . Magnified 1000 diameters. Large amount of granular pearlite, small amount of free ferrite.



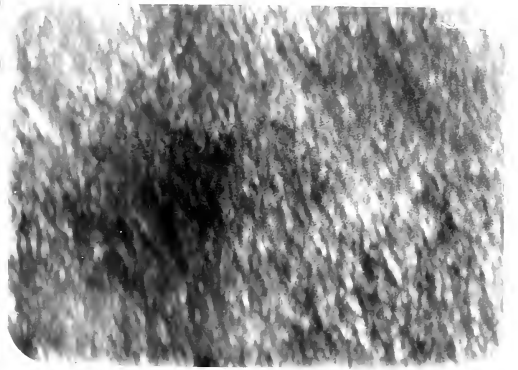
No. 15 - .29 carbon. Annealed at 640 , quenched from 875 , drawn to 450 . Magnified 1000 diameters. Large amount of laminated pearlite, small amount of free ferrite.



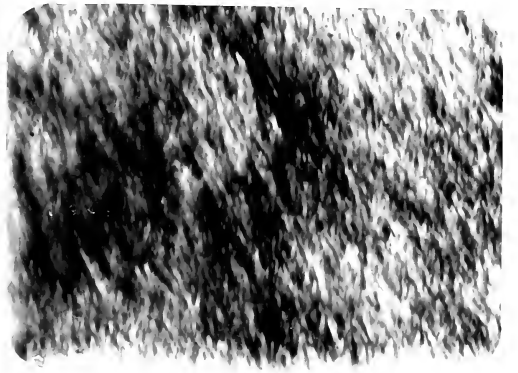
No. 19 - .29 carbon. Annealed at 840 , quenched from 900 , drawn to 450 . Very fine structure of laminated pearlite with a small amount of free ferrite. Magnified 1000 diameters.



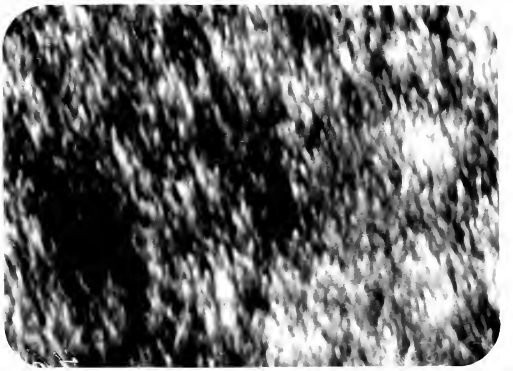
No. 36 - .47 carbon. Annealed at 820 . Magnified 1000 diameters. Coarse structure of granular pearlite and free ferrite.



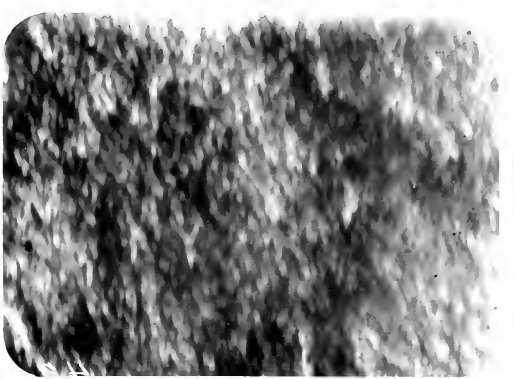
No. 38 - .47 carbon. Annealed at 820 , quenched from 790 , drawn to 475 . Magnified 1000 diameters. Small amount of free ferrite, large amount of granular pearlite and sorbite.



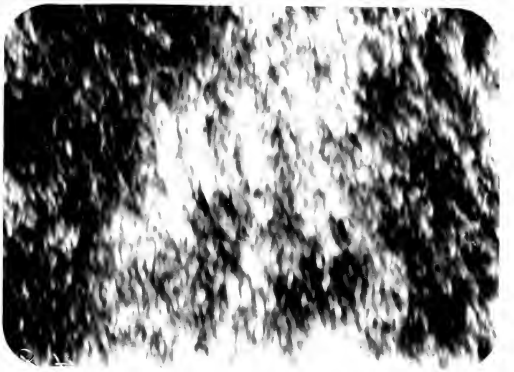
No. 42 - .47 carbon. Annealed at 820 , quenched from 825 , drawn to 475 . Magnified 1000 diameters. Sorbite, granular and laminated pearlite, small amount of free ferrite.



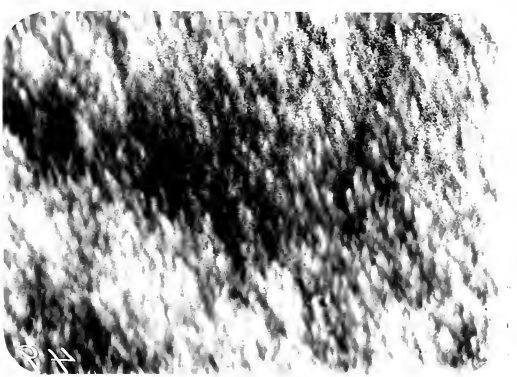
No. 46 - .47 carbon. Annealed at 820 , quenched from 850 , drawn to 450 . Magnified 1000 diameters. Small amount of free ferrite, sorbite and laminated pearlite, large amount of granular pearlite.



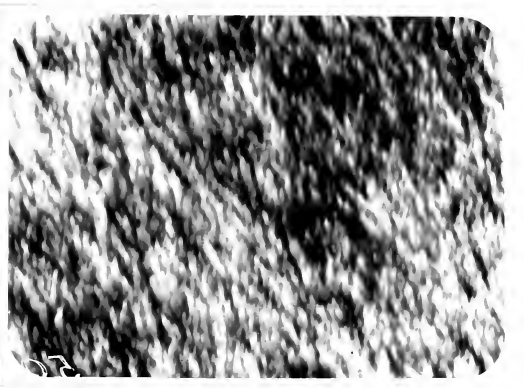
No. 47 - .47 carbon. Annealed at 820 , quenched from 850 , drawn to 500 . Magnified 1000 diameters. Very small amount of free ferrite, granular pearlite.



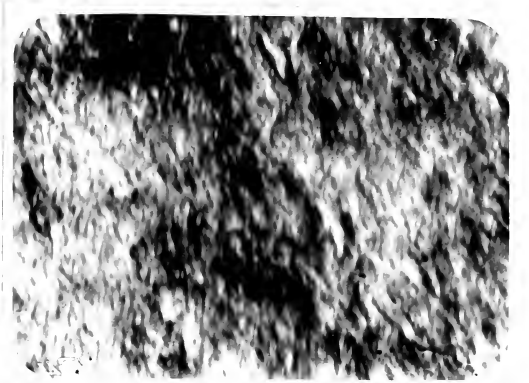
No. 48 - .47 carbon. Annealed at 820 , quenched from 850 , drawn to 550 . Magnified 1000 diameters. Free ferrite, granular and laminated pearlite.



No. 49 - .47 carbon. Annealed at 820 , quenched from 850 , drawn to 600 . Magnified 1000 diameters. Almost uniform structure of granular pearlite.



No. 50 - .47 carbon. Annealed at 820 , quenched from 875 , drawn to 450 . Magnified 1000 diameters. Laminated and granular pearlite.



No. 54 - .47 carbon. Annealed at 820 , quenched from 900 , drawn to 450 . Magnified 1000 diameters. Granular and laminated pearlite, small amount of sorbite and free ferrite.

CAL TESTS

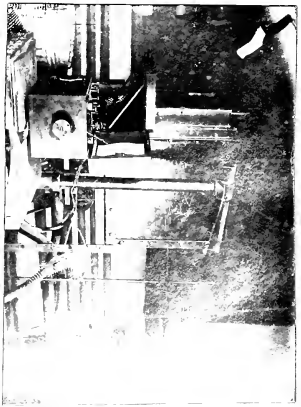
RECORD OF HEAT TREATMENTS AND PHYSICAL TESTS

CAL TESTS

FILE NO 3

RECORD OF HEAT TREATMENTS AND PHYSICAL TESTS

FORM NO 3



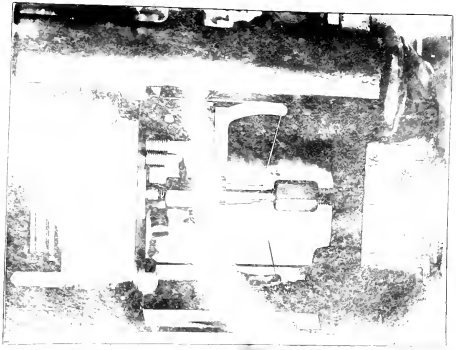
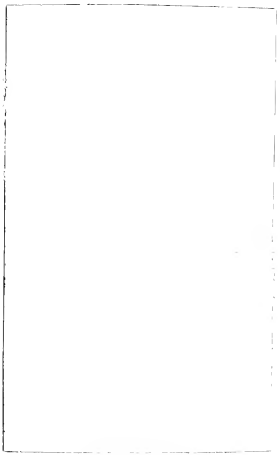
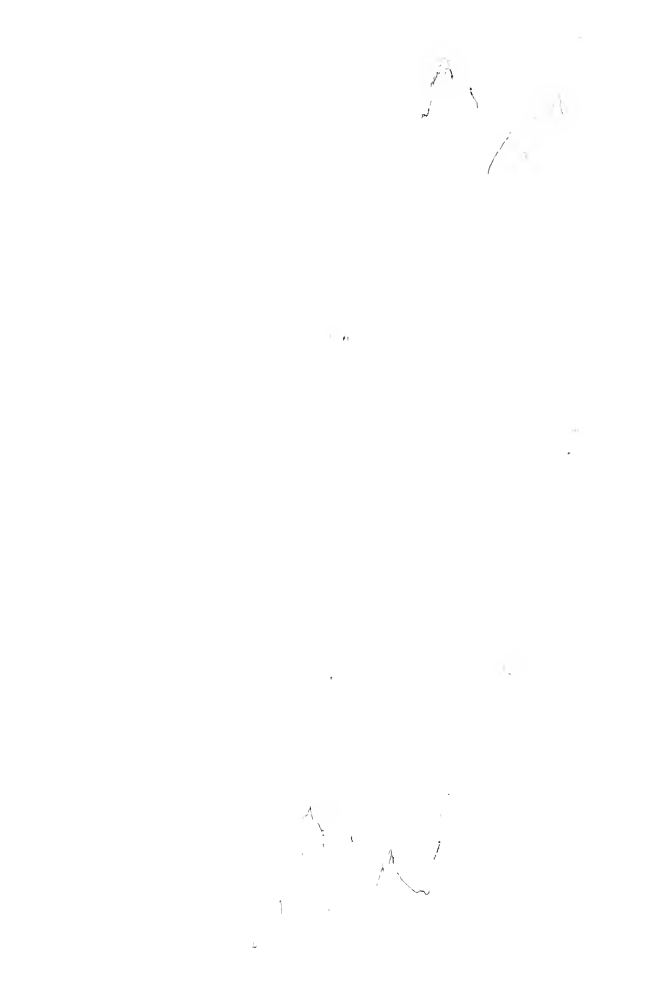


Plate No. 2





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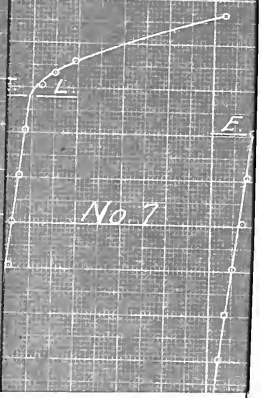

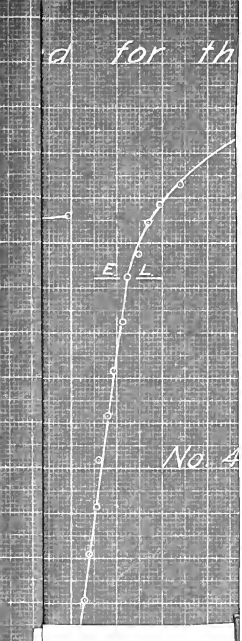
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No. 4